LITHIUM LENS (II)

Lithium Flow Magneto-Hydrodynamics

Progress report on Cornell Activity in Positron Production Scheme for ILC

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Institute of High Energy Physics, Beijing, China

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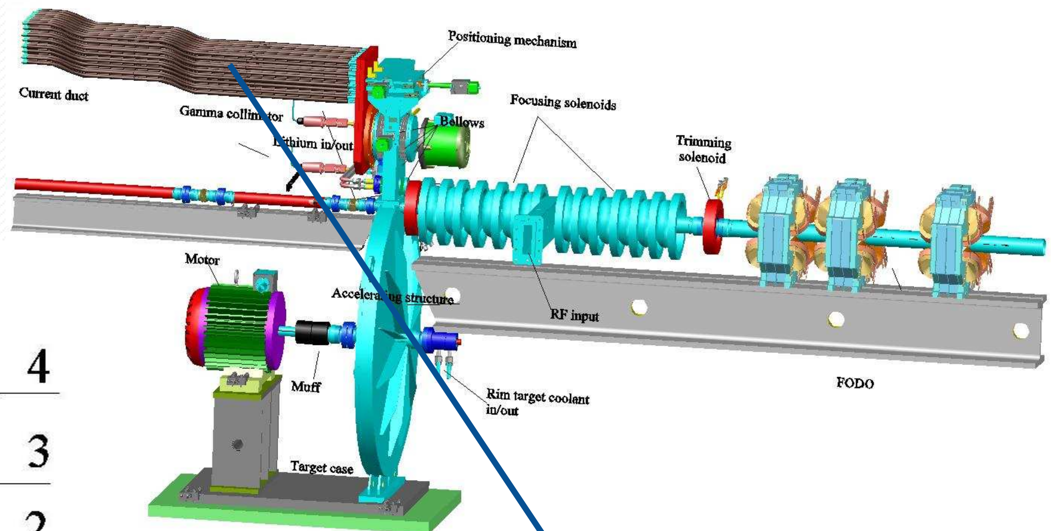
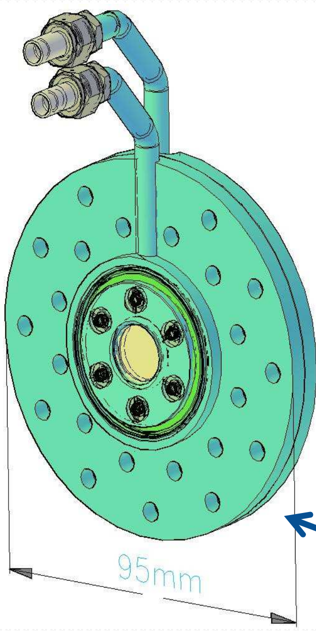
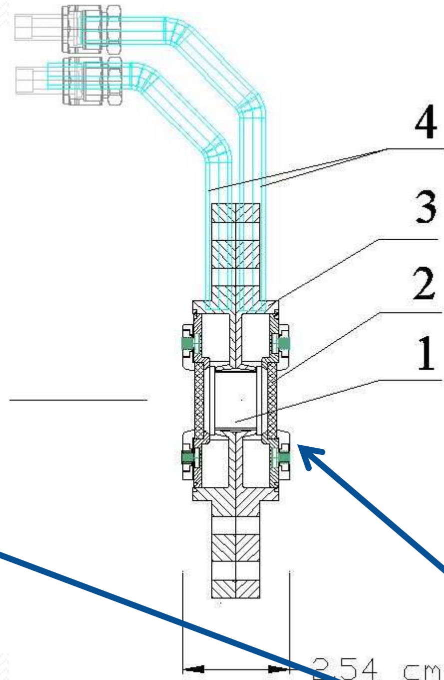
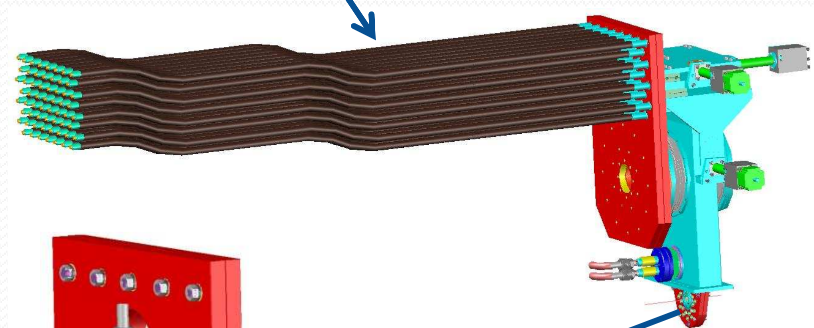
A.Mikhailichenko," *Lithium Lens (I)* ", CBN -09-4, Aug 2009, 17pp.

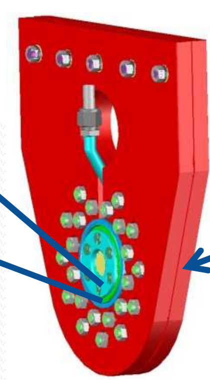
http://www.lepp.cornell.edu/public/CBN/2009/CBN09-4/CBN%2009-04.pdf











1–volume with Lithium, 2–window (Be/BC/BN), 3–electrical contacts with caverns for Li, 4–tubing for Lithium in/out

Activities

Was considered:
Conceptual design
Windows attachment
Energy Deposition in lens

Magnetic field in surroundings
Lithium Flow
Pressure dynamics
Some engineering for prevention of current flow though lithium duct

More to do:
Stress-strain in windows
Shock waves due to single bunch
Radiation damage conclusion (+remote handling etc)
Drawings for critical components: (feed-through, Lithium duct)

} Support required

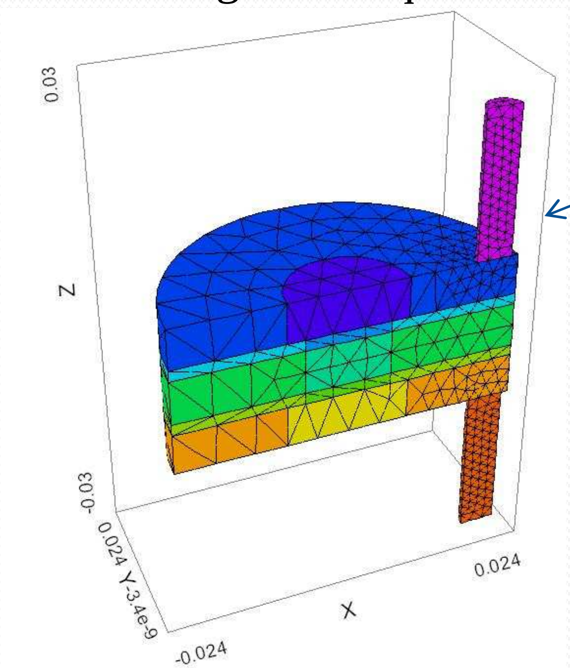
See for latest in:

A.Mikhailichenko, *"Lithium lens (II). Lithium Flow Magneto-Hydrodynamics"*, *CBN 10-3*, *http://www.lns.cornell.edu/public/CBN/2010/CBN10-3/CBN_10-3.pdf*

Set of equations used for modeling could be grouped into three categories: ***Electromagnetic*, *Hydrodynamic*** **and** ***Thermodynamic***.

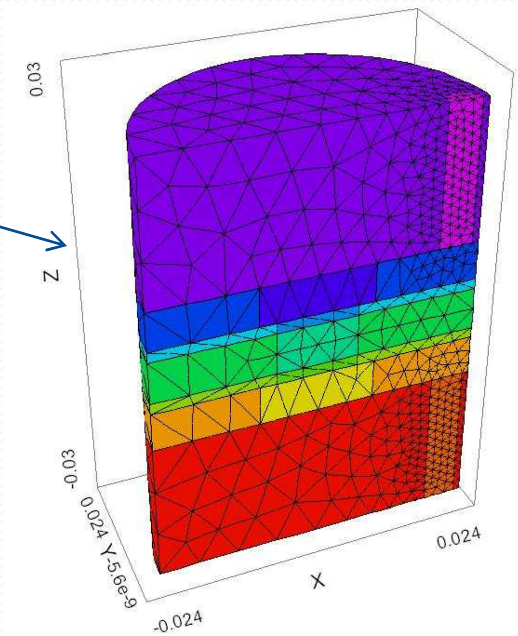
All three have cross terms linking electric current, fluid flow and temperature relaxation due to thermo-conductivity, Ohmic heating, fluid motion and frictional heat generation due to viscose phenomena.

For solving set of equation we used Partial Differential Equation Solver FlexPDE

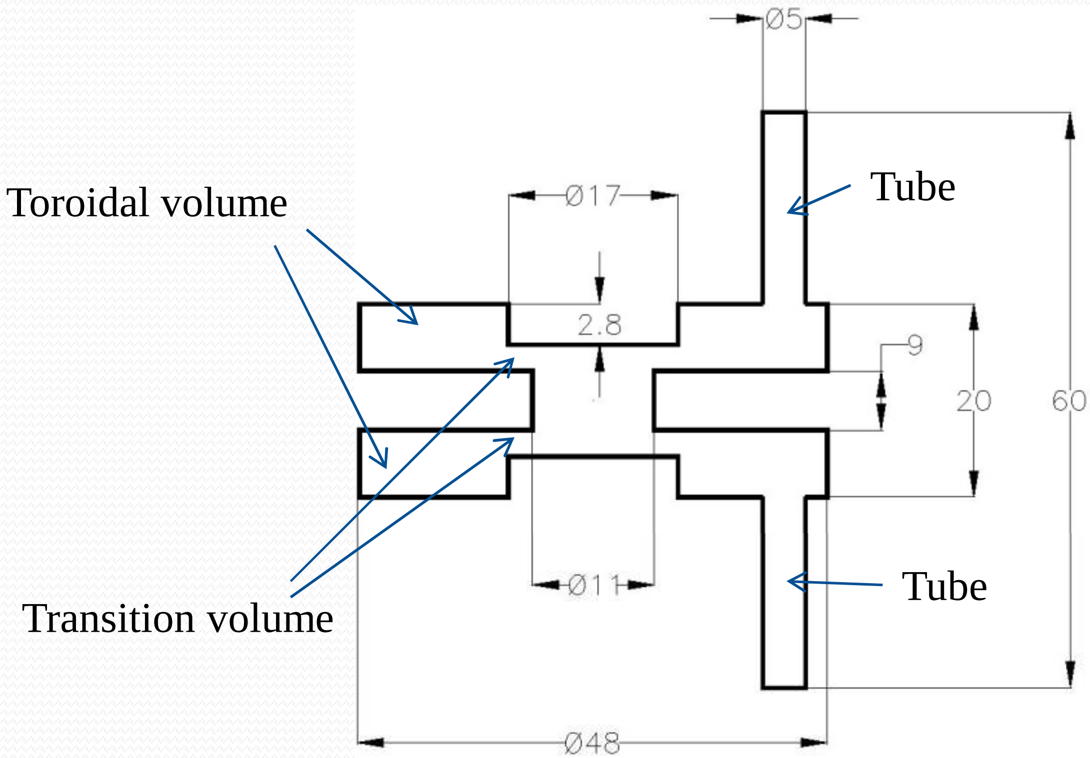


Model 1 and Model 2 use the same equations; model 2 has no mesh in upper and lower layers, sometimes we excluded even volume occupied by windows.

Boundary conditions applied on each surface



Dimensions of model



Dimensions of model, *mm*. All dimensions are subject of optimization process.

In volume without material artificial values for electric conductivity, viscosity, heat conductivity and density were applied:

layer 'down' sigma=1e-15 visc=1e10 k=1e-15 density=1e10
layer 'up' sigma=1e-15 visc=1e10 k=1e-15 density=1e10

Electromagnetism:

We used *voltage* as given parameter (<5V).

Set of equations:

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - grad(U) \quad \vec{B} = rot(\vec{A}) \quad \vec{B} = \mu \cdot \vec{H} \quad \vec{j} = \sigma \cdot (\vec{E} + \vec{v} \times \vec{B}) \quad div(\vec{j}) = 0$$

$$div(grad(A_x)) + \mu \cdot j_x = 0 \quad div(grad(A_y)) + \mu \cdot j_y = 0 \quad div(grad(A_z)) + \mu \cdot j_z = 0$$

Total energy deposition into the lens by feeding current during time ΔT can be calculated as

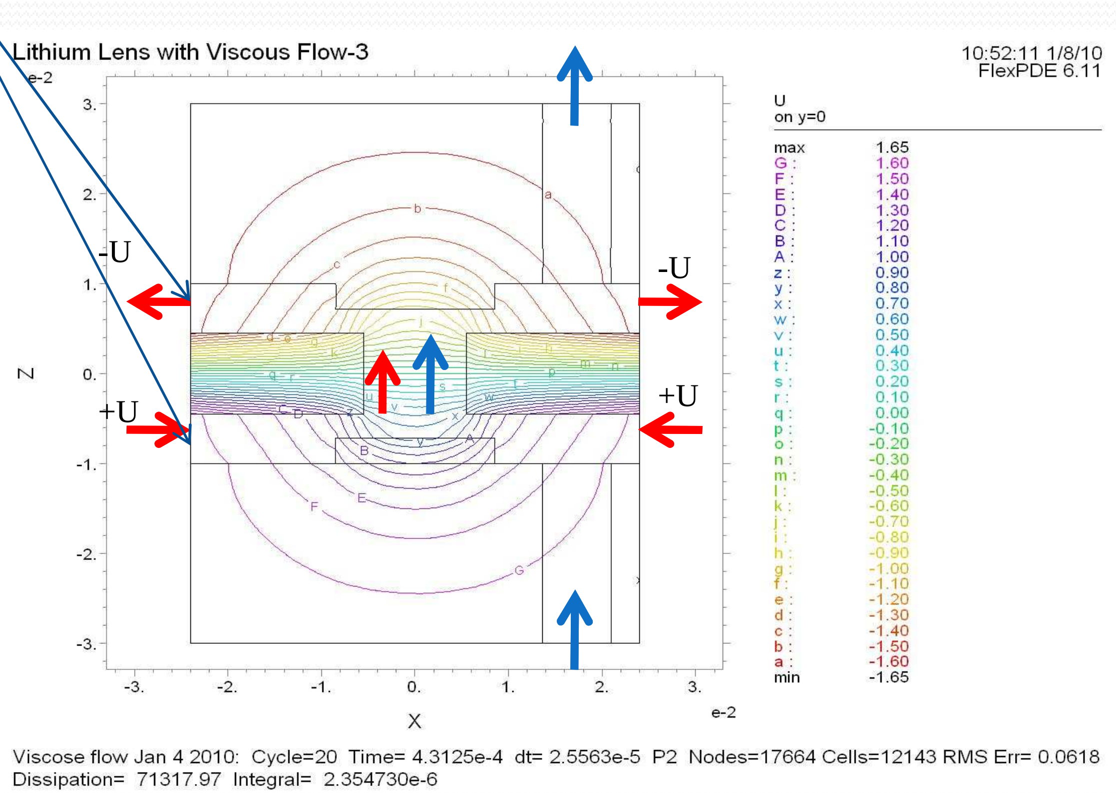
$$\Delta Q_{tot} = \int_0^{\Delta T} dt \int_V (\vec{j} \cdot \vec{E}) dV = \int_0^{\Delta T} dt \int_V \frac{j^2}{\sigma} dV \qquad (\approx 680 \text{ Joules})$$

$$div(\vec{j}) = -\left(div(\sigma \cdot \frac{\partial \vec{A}}{\partial t}) + div(\sigma \cdot grad(U)) + div(\sigma \cdot (\vec{v} \times \vec{B})) \right) = 0$$

$$div(grad(A_x)) + \mu \cdot j_x = div(grad(A_x)) - \mu \cdot \sigma \frac{\partial A_x}{\partial t} - \mu \cdot \sigma \cdot \frac{\partial U}{\partial x} + \mu \cdot \sigma \cdot (\vec{v} \times \vec{B})_x = 0$$

Parabolic (diffusion) equation: skin layer etc

Voltage applied to cylindrical surfaces



Potential. By blue arrows it is shown the Lithium flow, by red-current.

Different combinations of directions (current/flow) were used.

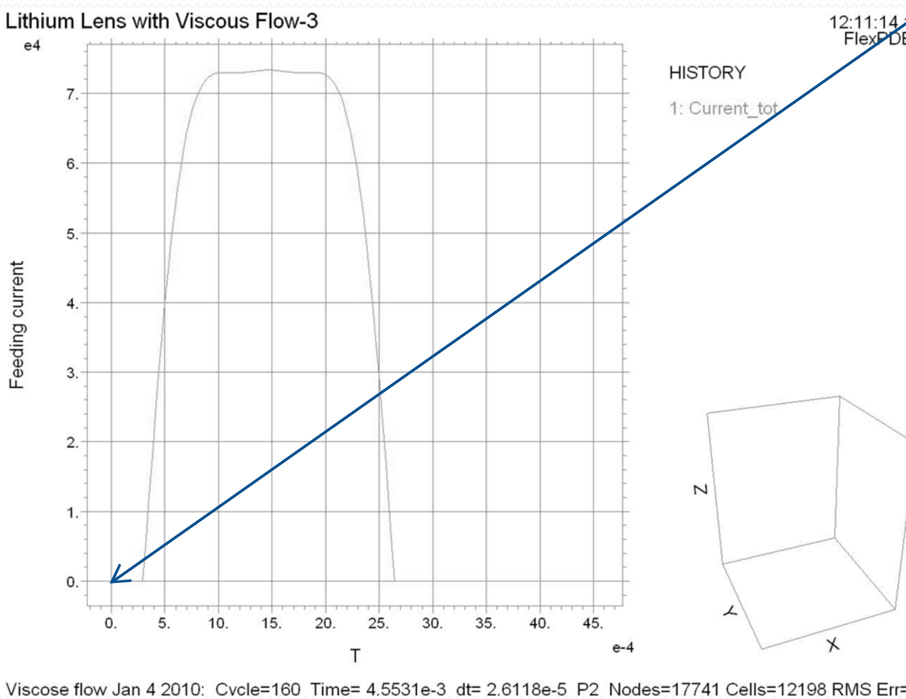
Voltage applied to the lens is a combination of three harmonics:

$$U(t) = U_0 \cdot [-4.5 \cdot Sin(\frac{\pi \cdot (t-\tau/10)}{\tau}) - 0.9 \cdot Sin(\frac{3\pi \cdot (t-\tau/10)}{\tau}) - 0.17 \cdot Sin(\frac{5\pi \cdot (t-\tau/10)}{\tau})] \quad [\text{Volts}]$$

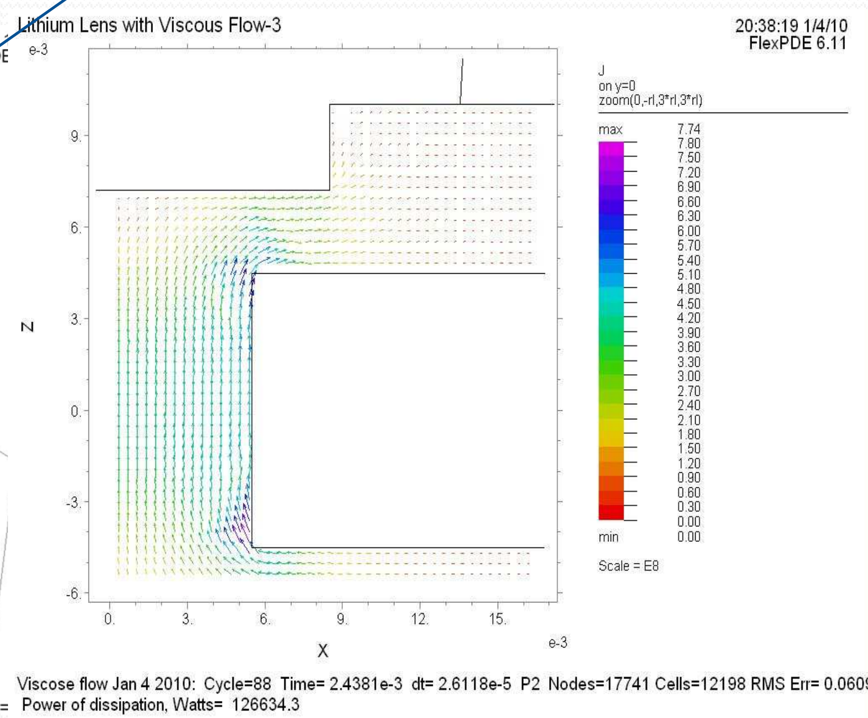
U_0=0.8

τ =2.3 *msec*

Pulse delayed by $\tau/10$

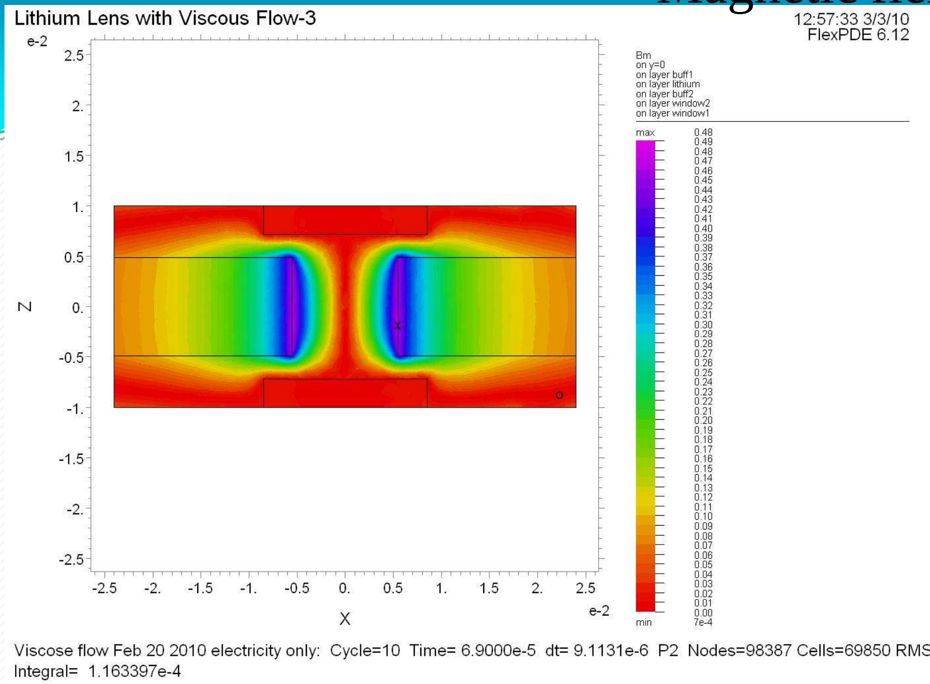


Electric current, *Ampers*.

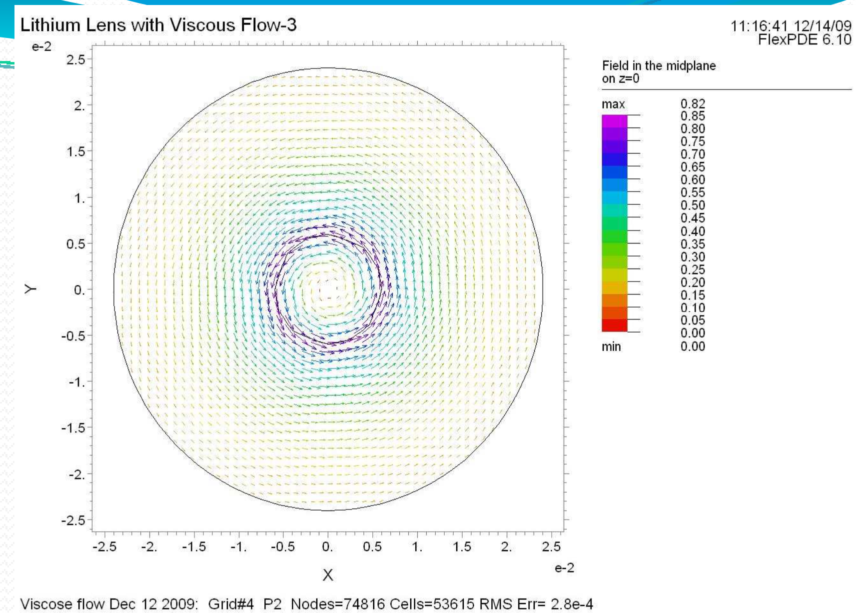


Vectors of current density. Value of current density represented by the length of arrows and theirs color.

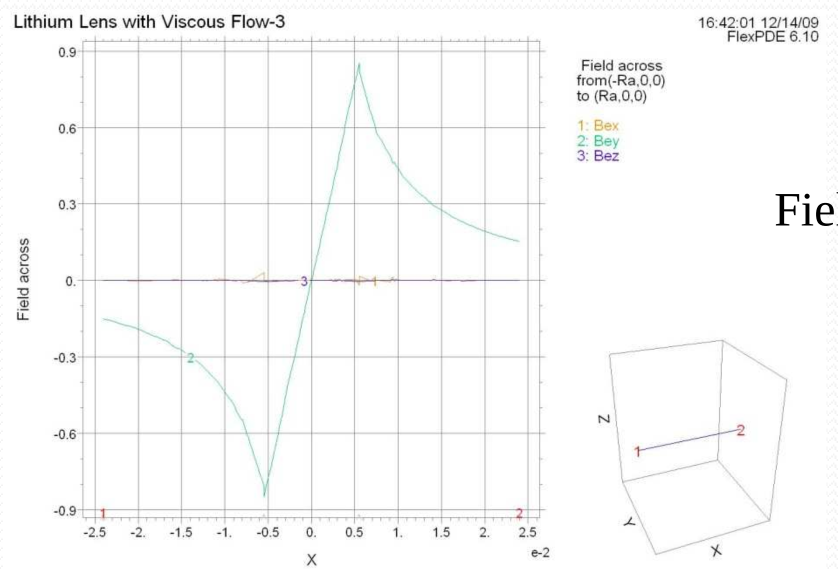
Magnetic field



Equal *B*-values counter plot



Vector plot of *B* in midplane of model.

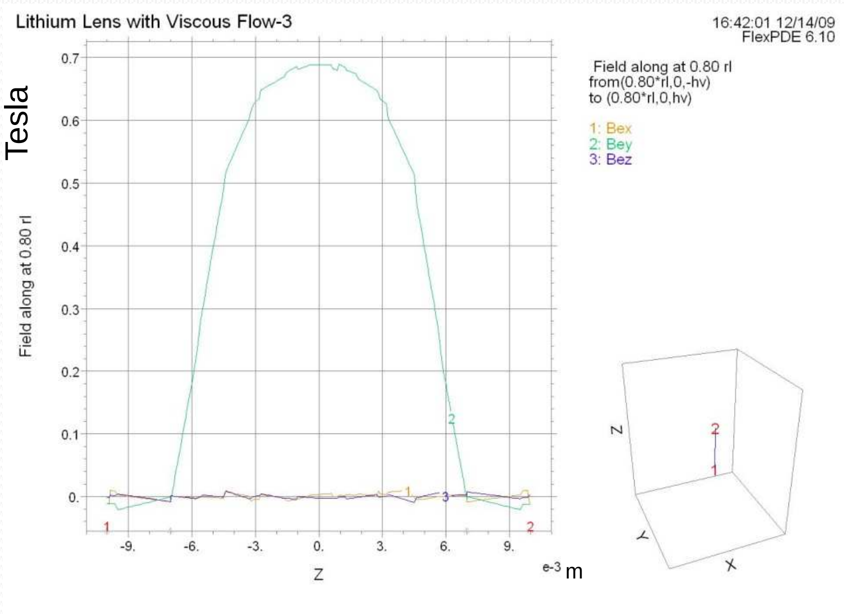


Field across through center

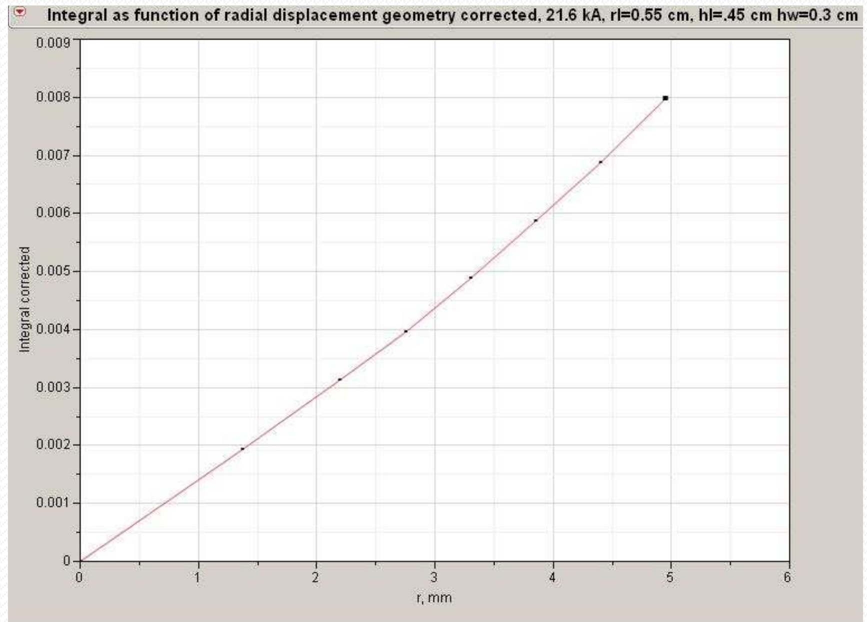
Some optimization of dimensions were done:

Increased length of Lithium cylinder from 0.6 to 1 cm;

Transition volume between cylinder and toroidal chamber squeezed;

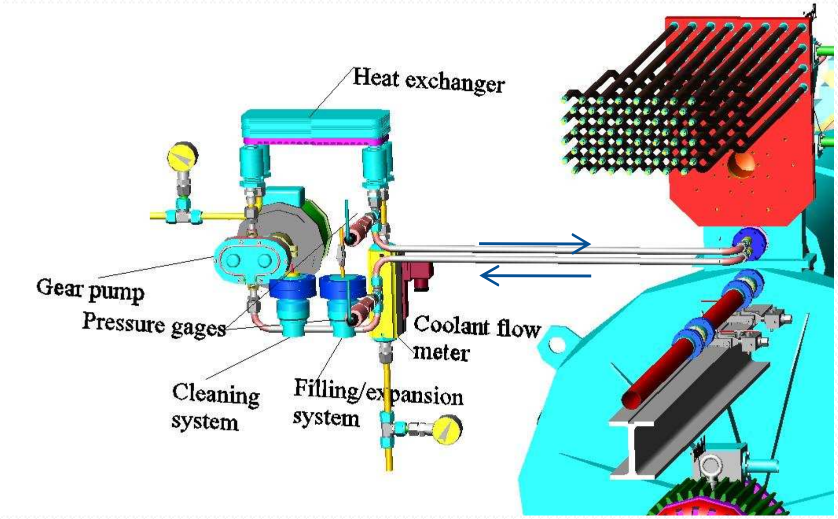


Longitudinal field dependence at 0.8 radius of lithium rod (which is 0.8x 5.5mm =4.4 mm)



Field integral as function of radial displacement

One comment



As the Lithium duct runs from inlet to outlet where the voltage applied, the current runs through the body of lens, but some fraction is running through the duct

Current runs not through the body of lens only, but through the Lithium duct (tubes, pump) also.

Length of duct ~2m, diameter ~ 7mm, so resistance is higher in $200/0.7^2$ ~400 times

So this back current is ~0.25% of the one running though the lens i.e. 70kA/400~175 A- not big, but it could be eliminated by insertion of non conducting interrupter, which is device similar to gear pump, but with non-conducting case and gears .

Lithium flow:

Flow of Lithium is governed by vector equation

viscosity — Second viscosity; not used

$$\rho \cdot \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla}) \vec{v} \right) + grad(P) - \eta \cdot \nabla^2 \vec{v} - \left(\zeta + \tfrac{1}{3}\eta \right) grad(div(\vec{v})) = (\vec{j} \times \vec{B})$$

In FlexPDE Grammatik components of velocity look like the following

vx: density*(dt(vx)+vx*dx(vx)+vy*dy(vx)+vz*dz(vx))+dx(p)-visc*div(grad(vx))= xcomp(cross(J,B))
vy: density*(dt(vy)+vx*dx(vy)+vy*dy(vy)+vz*dz(vy))+dy(p)-visc*div(grad(vy))= ycomp(cross(J,B))
vz: density*(dt(vz)+vx*dx(vz)+vy*dy(vz)+vz*dz(vz))+dz(p)-visc*div(grad(vz)) = zcomp(cross(J,B))

FlexPDE-version 6 allows writing this system as single vector equation

density*(dt(v)+dot(v,grad(v)))+grad(p)-visc*div(grad(v)) – $^1/_3$*visc*grad(div(v))=cross(J,B)

For pressure

$$div(grad(P))\left\{ -\frac{1}{c_B^2}\frac{\partial^2 P}{\partial t^2} \right\} = div(\vec{j} \times \vec{B}) - \rho \cdot div\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \vec{\nabla})\vec{v} \right) + C\eta \cdot div(\vec{v}) \left\{ -\Gamma \cdot \ddot{Q}(\vec{r}, t) \right\}$$

Not used in this modeling

FlexPDE:

p: div(grad(p))=density*div(dt(v)+dot(v,grad(v)))+div(cross(J,B))+1e5*visc/r^2*div(v) +visc/3*div(grad(div(v))) {+1/c02*dt(dpt)-G/c02*Qdott }

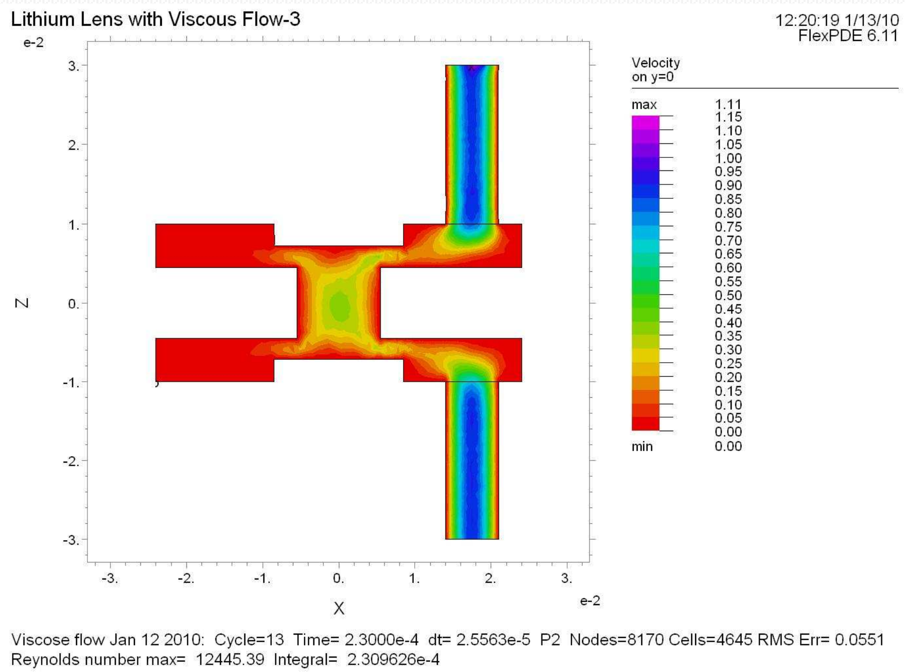
Velocity

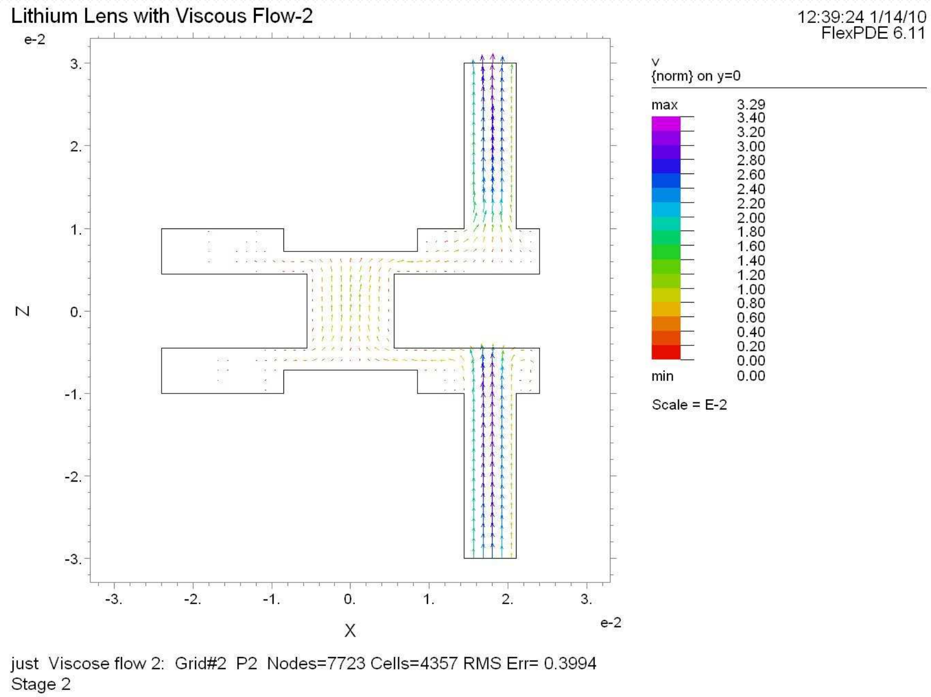
Pressure rises smoothly:

p_out= IF t<tau/10 THEN p_in-delp*10*(t/tau) else p_in-delp

tau $\equiv \tau = 2.3 ms$

Pressure drop

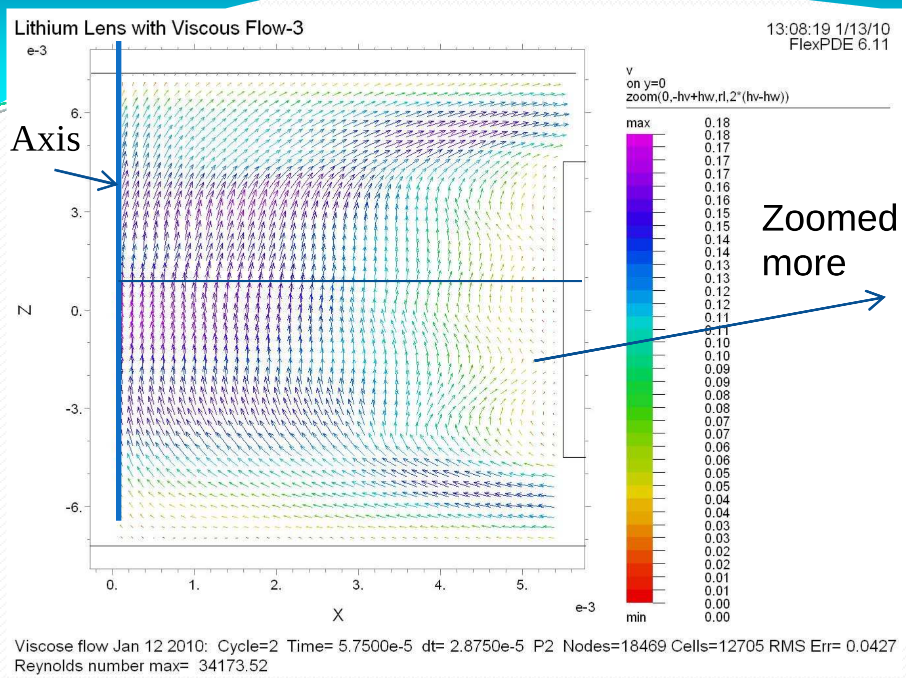


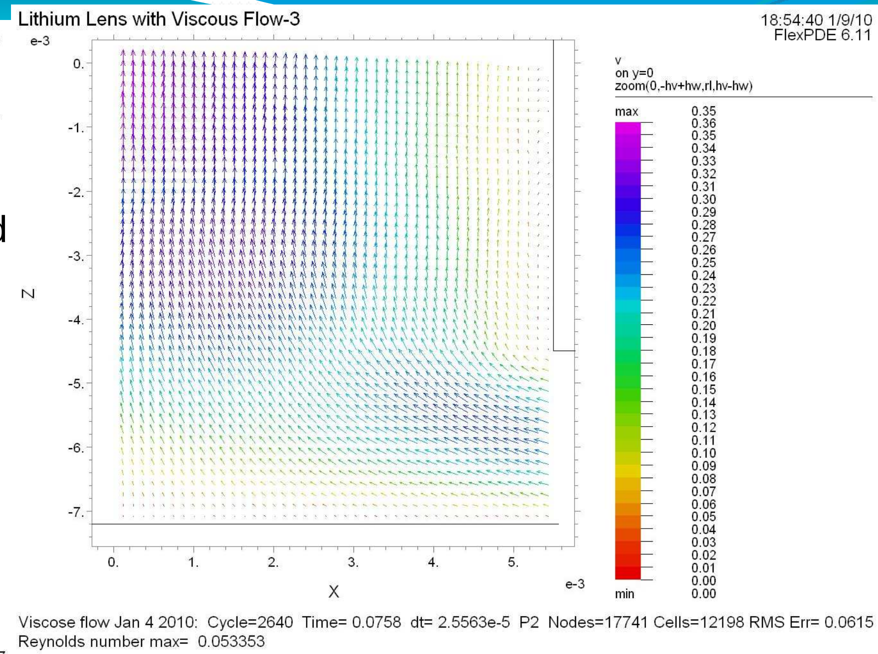


Contour of Lithium velocity module; no electrical current yet.

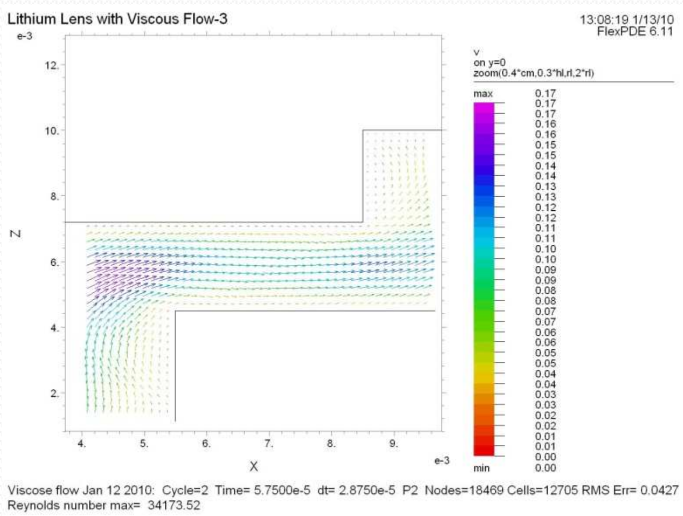
Vectors of velocity; no electrical current yet.

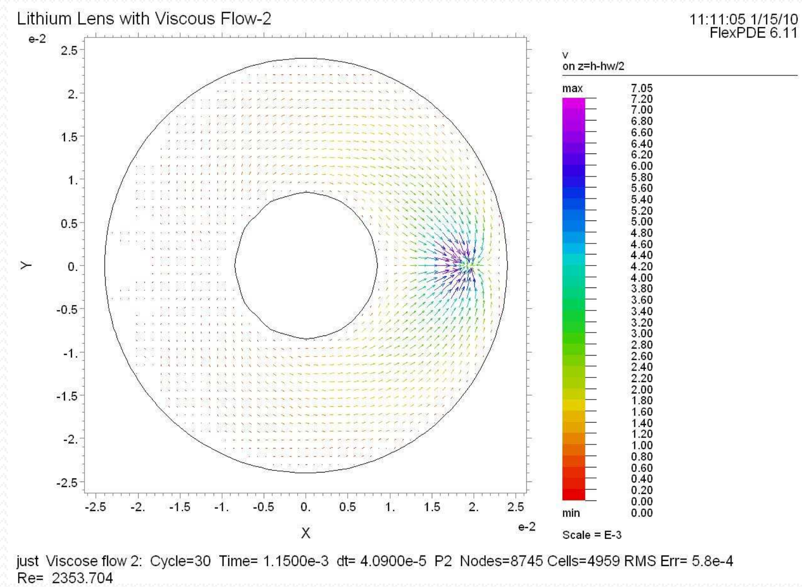
Without current





Vectors of velocity zoomed

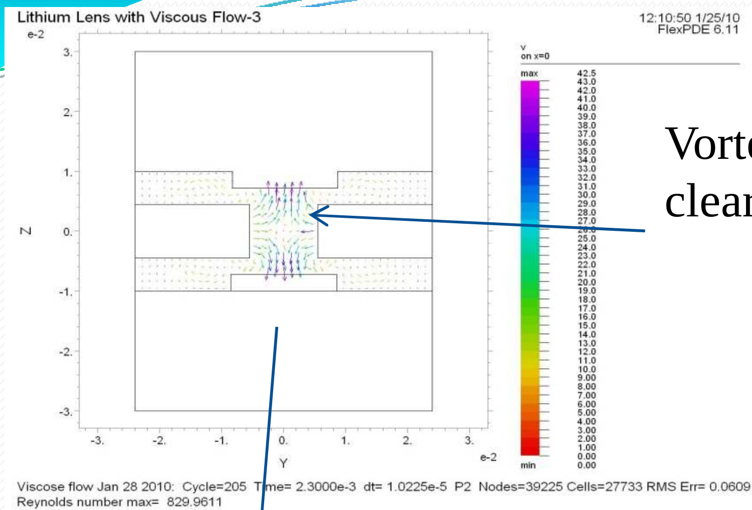




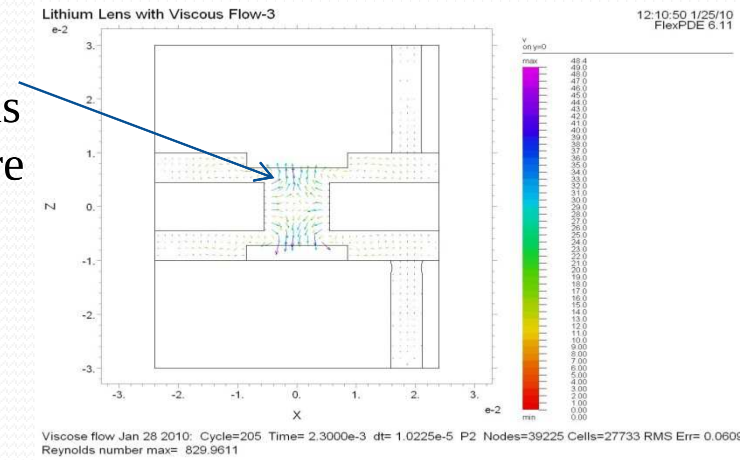
Vectors of velocity in transition volume

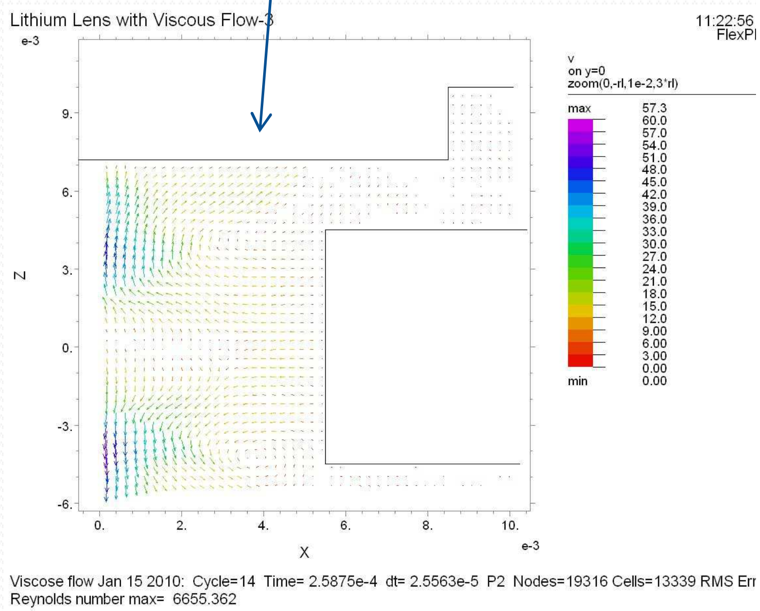
Vectors of velocity just below outlet tube

With current

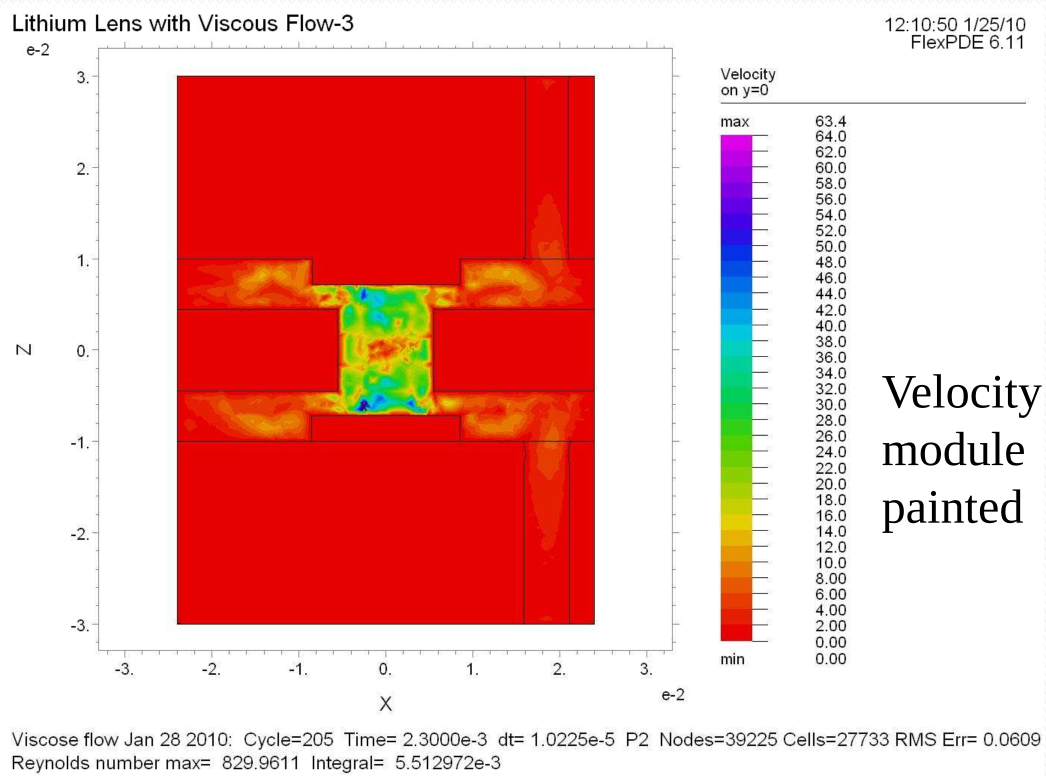


Vortex motion is clearly seen here



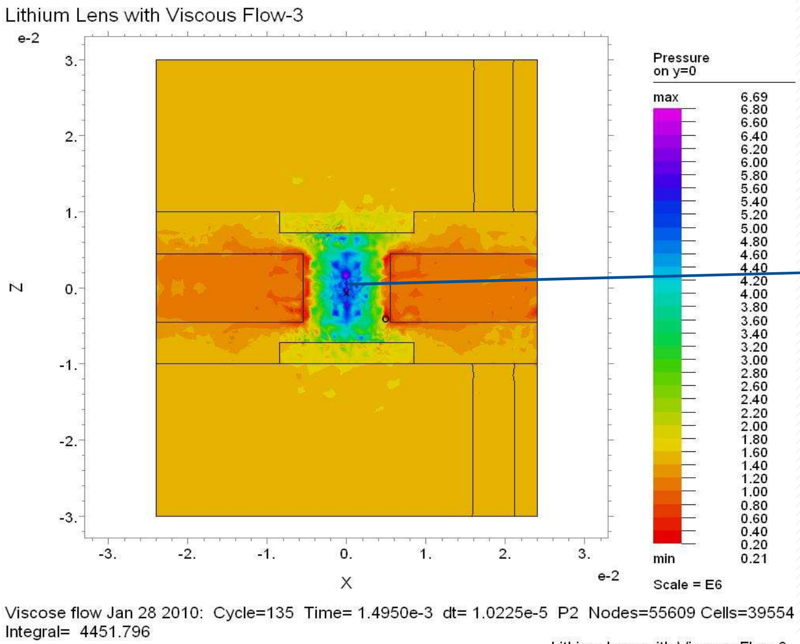


Zoomed

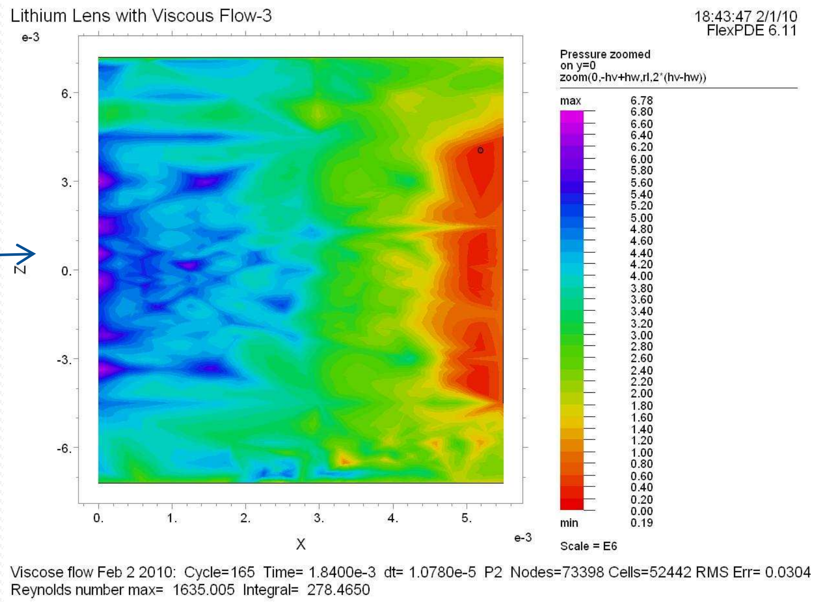


Velocity module painted

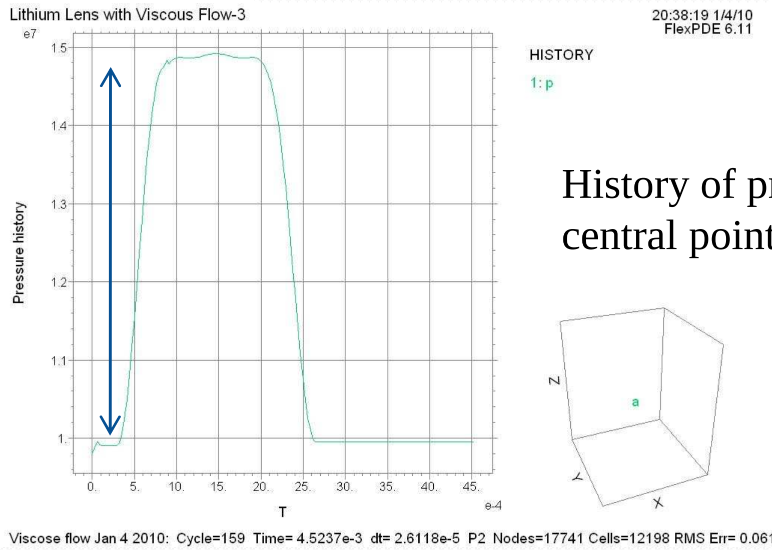
Pressure



Zoomed



Jump ~$5x10^6$Pa ~50*atm*



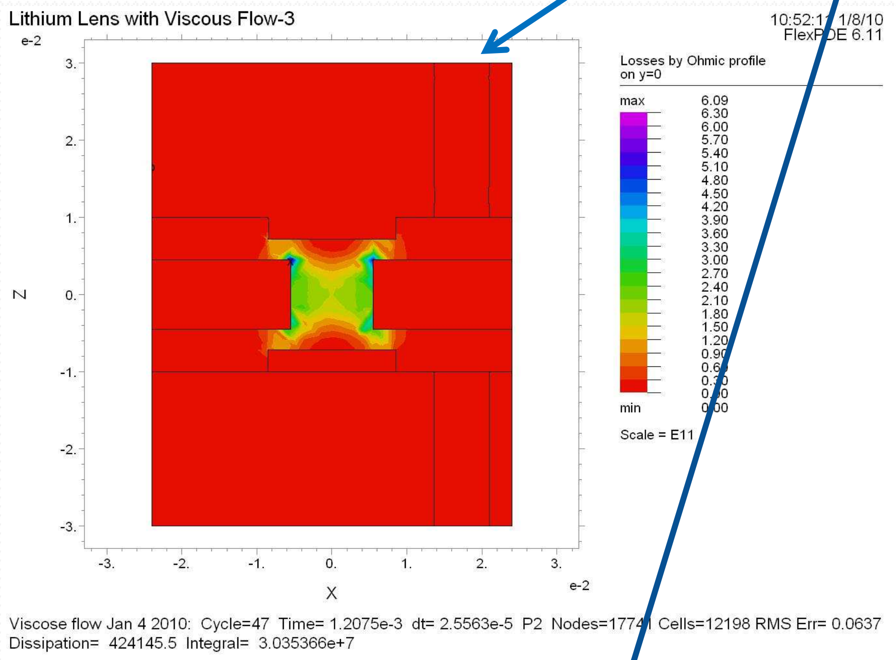
History of pressure at central point.

Temperature:

$$\rho \cdot C_p \left(\frac{\partial T}{\partial t} + \vec{v} \cdot grad(T) \right) - div(k \cdot grad(T)) + P \cdot div(\vec{v}) = (\vec{j} \cdot \vec{E}) + \sigma'_{ik} \frac{\partial v_i}{\partial x_k} \{+\dot{Q}(\vec{r}, t)\}$$

Beam; not used here

Ohmic losses.

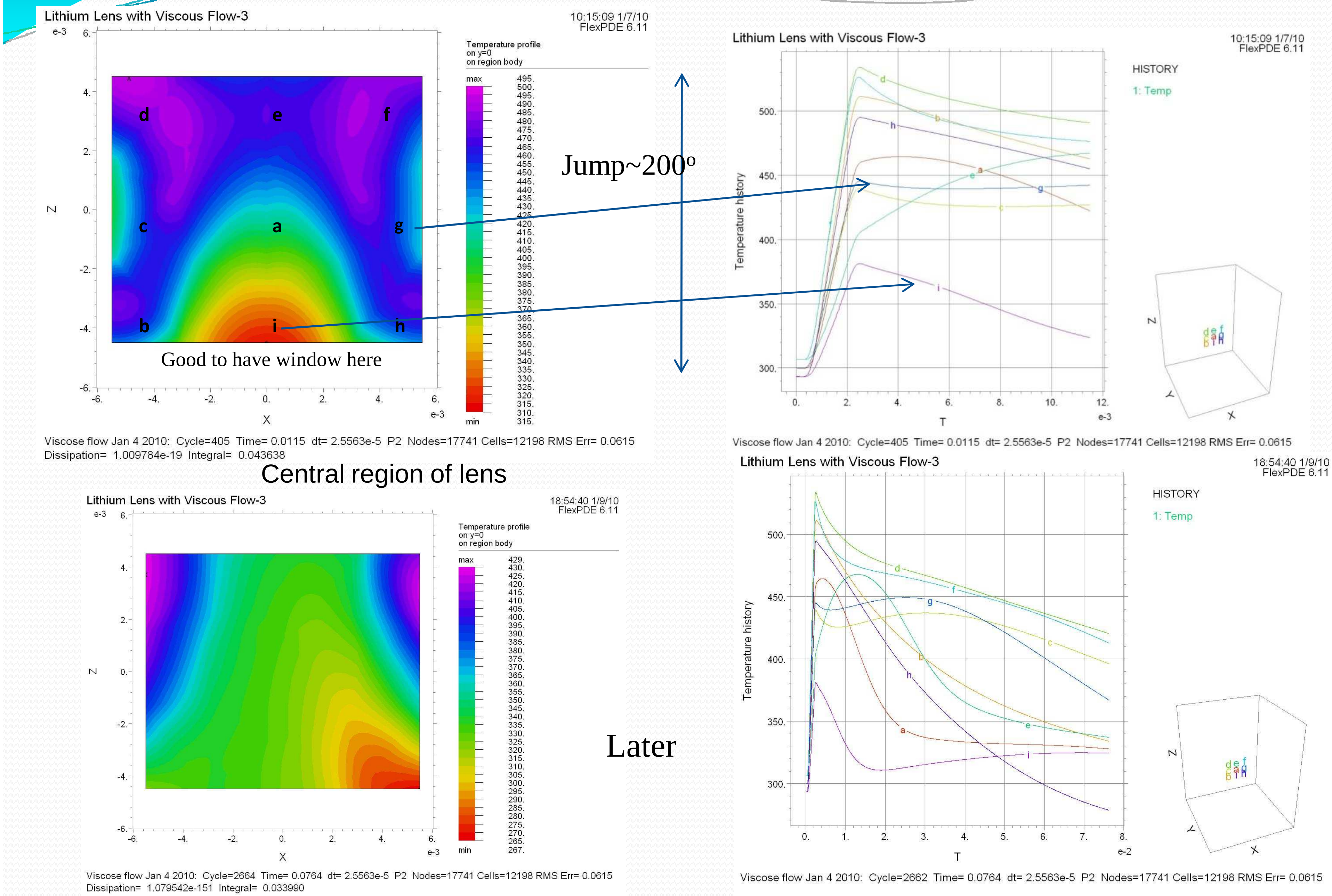


$$phi = \sigma'_{ij} \frac{\partial v_i}{\partial x_j} = \eta \frac{\partial v_i}{\partial x_j} \left[\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \tfrac{2}{3} \delta_{ij} \frac{\partial v_k}{\partial x_k} \right) + \zeta \cdot \delta_{ij} \frac{\partial v_k}{\partial x_k} \right] =$$

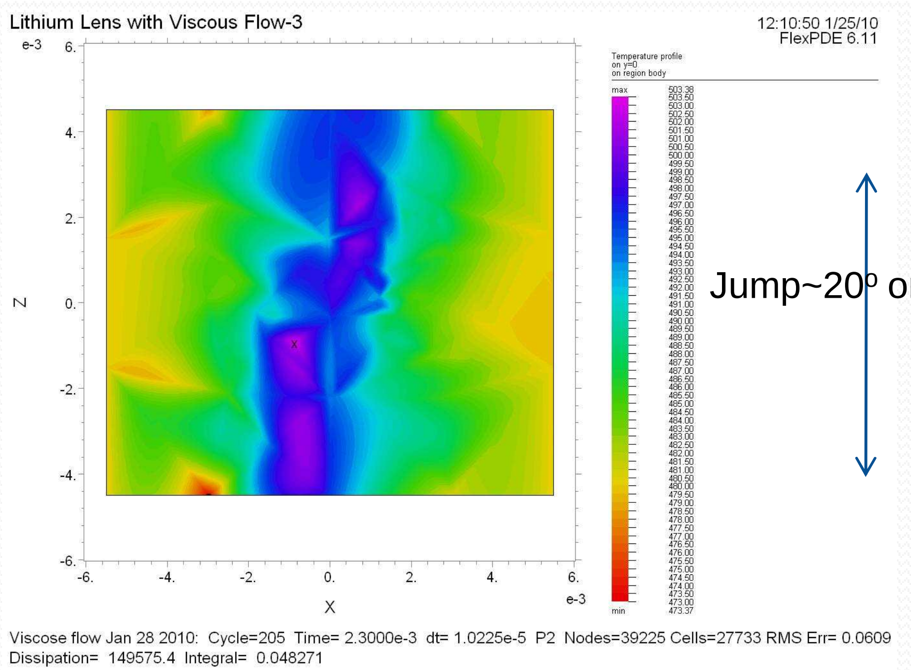
$$2\eta \left[\left(\frac{\partial v_x}{\partial x} \right)^2 + \left(\frac{\partial v_y}{\partial y} \right)^2 + \left(\frac{\partial v_z}{\partial z} \right)^2 + \frac{1}{2} \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y} \right)^2 + \frac{1}{2} \left(\frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z} \right)^2 + \{ \zeta \cdot (div(\vec{v}))^2 \} \right]$$

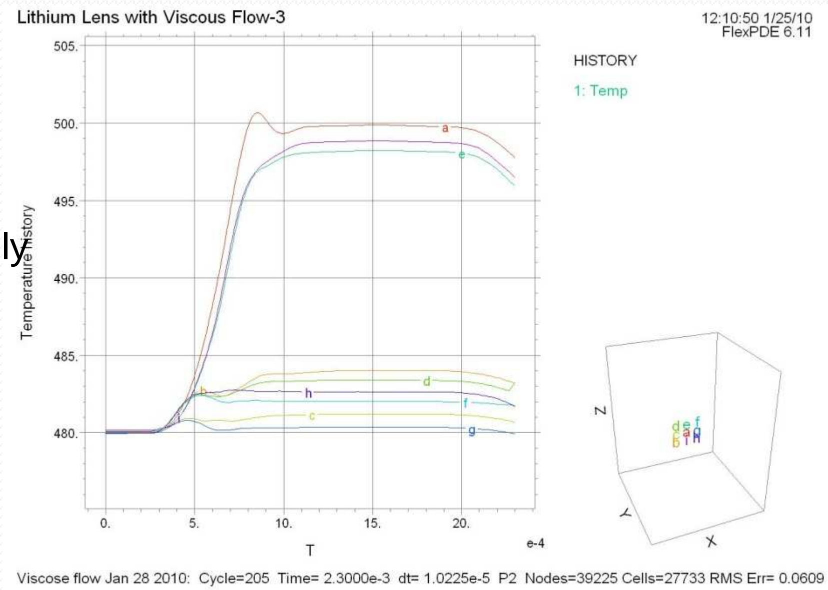
Not used in this run

Temperature history and profile, when only inlet/outlet temperature is fixed



Temperature history and profile, when **all** walls kept at the same temperature 480°K





Hot fractions located in central region

Temperature history

So all Lithium case is keeping at fixed temperature, the temperature jump of Lithium is minimal.

SUMMARY

Vortex circulation of liquid Lithium due to magnetic force helps in reduction of temperature in central region of windows, thanks to forced mixing.

Calculated pressure and temperature profiles confirmed that parameters of lens are technically reasonable. Generally, the temperature rise is below 50^{o}C coming to a total of ~100 ^{o}C with beam as the beam duty of train is ~1 msec. So far there is no indication of cavitation.

We recommend increase of length of space occupied by Lithium (in direction along the beam pass) to ~1 *cm* (from~0.6cm). This brings reduction of current to ~70 kA.

We also slightly modified the configuration of junction between Lithium cylindrical container and the buffer toroid-like volume. This improved linearity of integrated field as function of transverse coordinate.

Numerical code developed allows further investigation of Lithium lens dynamics and easy modification of geometry.

Stress-strain in windows, Shock waves and Cavitations introduced by the beam will be investigated in future, while funds allow.

Usage of FlexPDE computer code looks adequate here.

Best test for liquid Lithium lens is fabrication of full scale prototype:

Tests with full scale prototype if is were to built:

1.Test of Lithium pump (electromagnetic vs mechanical pump)
2. Best conditions for Lithium flow (pressure, pressure drop)
3. Thermal conditions (insulation, cooling, temperature control)
4. Starting procedure (warming, pumping start)
5. Full scale Power Supply (single thyristor, duct; *this PS is good for Flux concentrator*)
6. Operation without beam (full current, repetition rate)
7. Test with beam (electron/positron/proton beam)

Just this one

Reverse Switched Dinistors (RSD) for peak current from 200 kA to 500 kA and blocking voltage of 2400 V, encapsulated in hermetic metal-ceramic housing and without housing (RSD sizes of 64, 76 and 100 mm)